CHAPTER 4

SATELLITE CONTRIBUTIONS TO THE OCEAN OBSERVING SYSTEM FOR CLIMATE

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Introduction

A recent workshop report begins with the sobering statement, "Measuring the small changes associated with long-term global climate change from space is a daunting task." (Ohring et al., 2004) However, with over three decades of satellite-based measurements and continued improvements to the quality and availability of these observations, there is now more reason than ever to expect satellites to fill a critical and unique role in the global ocean observing system for climate. Satellites, with their ability to make global observations on a frequent basis, provide a dimension to the ocean climate observing system that would be impractical or impossible to achieve with in situ platforms alone. These frequent, global observations are in many cases made at very fine spatial resolutions, enabling many new climate-ecosystem interaction studies as well as enhancing traditional climate science.

Making effective use of satellites as climate platforms requires overcoming several technical and scientific challenges. For example, numerous Advanced Very High Resolution Radiometers (AVHRRs) have flown on board the series of NOAA polar orbiting satellites for more than 20 years. Despite the similarities of the sensors, each behaves differently and each rides on a satellite whose characteristics differ from the others in the series. Adding to this challenge, both the instrument responses and the platform characteristics can and do change over time. Additionally, to detect typically small climate signals, climate-quality algorithms must be developed iteratively, continually improving over operational, near real time algorithms. All of these challenges must be overcome if a credible, consistent record is to be generated.

In addition to the scientific and technical challenges, several organizational difficulties must also be resolved. Generating *climate data records* (CDRs), defined as a time series of sufficient length, consistency, and continuity to determine climate variability (NRC, 2004), requires a sustained, ongoing commitment to regularly reprocess the entire satellite time series using the latest available algorithms and techniques. Steps must be taken to insure guidance and feedback from the community is incorporated in the CDR generation process. To generate the best possible CDRs, data may be required from satellites operated by different agencies or countries requiring a high level of national and international coordination. These and other organizational and institutional challenges must be met to insure optimal satellite contributions to the ocean observing system for climate.

In addition to meeting these challenges, environmental observations from satellites must always be viewed as fundamentally integrated with and dependent on in situ measurements if their value is to be fully realized. All satellite observations require in situ measurements in algorithm development, quality control, instrument characterization, and validation. Neither in situ nor satellite based observations can be relied on alone if a full understanding of the complex climate system is to be achieved. One example of the tight connection between in situ and satellite platforms is the Marine Optical Buoy (MOBY), which supports the in situ validation of satellite ocean color estimates from space. Another area where satellites and in situ measurements work together to observe climate change is the determination of sea level rise, where both satellite altimeters and in situ tide gauge networks are used. Satellite reprocessing efforts such as the Pathfinder project discussed below, which work to produce longer, more consistent and accurate data streams, rely heavily on large numbers of moored and drifting in situ buoys to calculate algorithm coefficients and conduct validation studies. In some areas, such as the determination of sea ice trends, gaps in the satellite record can only be filled by in situ observations of sea ice concentration. These examples and many more point to the need to maintain both satellite and in situ observing and reprocessing capabilities.

Satellite based observations of the oceans have already begun contributing to the climate observing system in many areas. Five of these areas are sea surface temperature (SST), ocean color, marine winds, sea surface topography, and sea ice. For each of these areas, a brief discussion of the importance of that parameter class to climate monitoring will be given along with a brief history and current status of the space-based sensors used to measure that parameter. Some example satellite products currently used will also be given along with a look forward into the future of measuring these parameters from space.

Sea Surface Temperature

Why Observe SST?

Of the many oceanographic parameters capable of being observed from space, SST is perhaps the single most important for climate monitoring. Satellite observations of SST variability and trends can be made at the global, regional, and even local level. These observations are used to measure the magnitude of ocean surface temperatures changes, initialize and validate numerical models, and understand the role of thermal stresses on marine ecosystems. An enormous diversity of applications and research studies rely on this critical parameter.

A Brief History

High quality infrared-based SST measurements have been made continuously since late 1981 when the five-channel AVHRR on the NOAA-7 polar orbiting satellite became available, but earlier attempts date back to 1972. The AVHRRs have now flown on 12 NOAA polar orbiters and provide the longest continuous time series of any satellite-based oceanographic parameter. Numerous other satellite sensors have also used infrared measurements to determine SST. In 1991, the European Space Agency launched the Along Track Scanning Radiometer (ATSR-1), followed by the ATSR-2 in 1995 and an improved version known as the Advanced-ATSR (AATSR) in 2002. These sensors employ a dual-view of the ocean surface, thereby permitting a highly accurate accounting of the errors introduced by the atmosphere. Geostationary satellite observations of SST are available from late 2000, using the NOAA Geostationary Operational Environmental Satellites (GOES), allowing repeated views of the ocean surface multiple times per day. In late 1999, NASA launched the first Moderate-resolution Imaging Spectroradiometer (MODIS) on board its Terra platform, and a second one on Aqua in 2002. Microwave observations, which have an important advantage in being largely unaffected by clouds and intervening atmosphere, have also been used to determine SST. The Tropical Rainfall Measuring Mission (TRMM) and its TRMM Microwave Imager (TMI) provide SSTs back to December of 1997. The Advanced Microwave Scanning Radiometer-EOS (AMSR-E), on board NASA's Aqua platform, also takes advantage of the nearly all-weather capability of the microwave portion of the spectrum. These observations are made at substantially coarser spatial resolutions than the infrared measurements to overcome the low microwave signal to noise ratio.

Present Status and a Look Forward

Currently, both MODIS sensors continue to function and the AVHRRs on board NOAA-17 and NOAA-18 are in operational status. GOES platforms continue to deliver SST measurements, as does the AATSR, TMI, and AMSR-E. Other platforms are also currently making SST observations. In the next several years, as part of the next generation National Polar-orbiting Operational Satellite System (NPOESS), the Conical-scanning Microwave Imager/Sounder (CMIS) and the Visible-Infrared Imager-Radiometer Suite (VIIRS) will carry on the time series established by the microwave platforms, the AVHRRs, and the MODIS sensors. Another AVHRR will also be on launched in 2006 on board the European MetOp platform and on the final in the series of current NOAA polar orbiters, carrying the SST observations from AVHRR forward several more years.

Critical Activities

This variety of SST observations from space highlights priority areas in SST science and CDR development activities: consistently reprocessing individual sensor observations, combining multiple contemporaneous observations from different sensors, and merging time series from individual sensors into a consistent record. Accomplishing these tasks to produce climate quality products requires, among many other things, a sophisticated understanding of diurnal variability to account for the different observation times of the various platforms and a quantitative determination of single-sensor uncertainties and biases between the different sensors and between the satellites and in situ observations, so they can all be effectively combined.

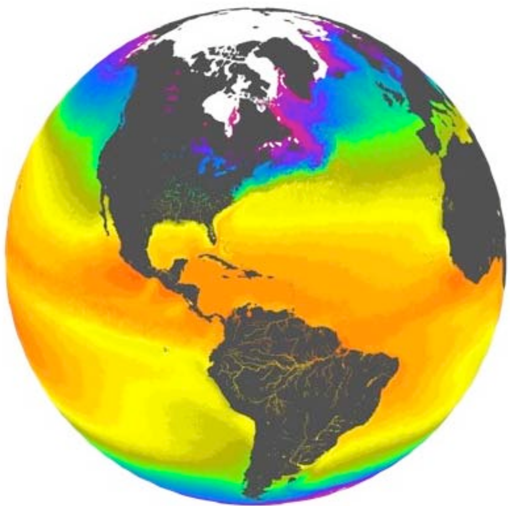

Figure 1: Climatological week 50 from 1985-2001 Pathfinder Version 5 SST data, with ice mask from w eek 50 of 2003. Developed using methods of Casey and Cornillon (1999).

Many of these issues are being addressed at both the national and international level. For example, NOAA's National Oceanographic Data Center, along with contributions from the NOAA Coral Reef Conservation Program, supported the AVHRR Pathfinder effort for the last four years (funding has expired and is now being sought to continue the project). Pathfinder is a single-sensor series reprocessing effort focused on creating global SST CDRs from the AVHRRs on the NOAA polar orbiters (http://pathfinder.nodc.noaa.gov). The Pathfinder project resulted in a global, 4 km resolution time series spanning 1985-2005 on multiple averaging periods (daily, 5-day, 7-day, 8-day, monthly, and yearly) with corresponding climatologies (Figure 1). The need for reprocessing efforts like this is clearly demonstrated in Figure 2, which illustrates the difference in SST trends between 1985 and 2004 determined using operational AVHRR SST data and Pathfinder AVHRR data. Taking the difference clearly highlights large regions of the global ocean where the trends differ by more than 0.1°C/year. These differences are as large as the observed trends during this period (note that globally averaged trends over the last 100 years are much smaller, on the order of 0.1°C/decade) and in some cases indicate regions where the sign of the trends are reversed relative to one another.

With a focus on other sensors, the commercial research company Remote Sensing Systems routinely conducts reprocessing of the TMI and AMSR-E SST products (http://www.remss.com). The European SST community has recently decided to begin a reprocessing of the entire ATSR and AATSR time series and NOAA's Office of Research and Applications works continually on improving SST estimates from the GOES platforms. These projects focus on observations from a single class of satellite sensor, while the international GODAE High Resolution SST project works to combine SST observations in both real time (http://www.ghrsst-pp.org) and in delayed mode for higher accuracy, climate quality products (http://ghrsst.nodc.noaa.gov).

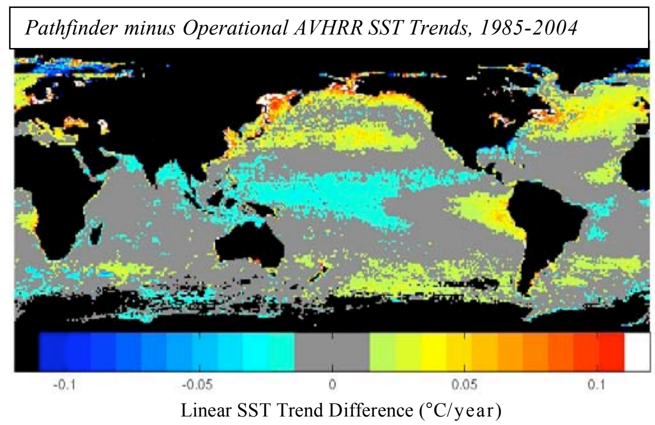

Figure 2: Pathfinder linear SST trends for 1985-2004 minus the corresponding Operational AVHRR linear trends. Trends are calculated on a weekly, one-degree grid. The trend differences are indicated in °C/year. Grey areas are where the differences are small (plus or minus 0.01 °C/year). Warm (cool) hues indicate areas where the Pathfinder trend is more (less) positive than the Operational AVHRR trend.

Ocean Color

Why Observe Ocean Color?

Satellite measurements of visible and reflected near infrared light result in the suite of products termed "ocean color". The color of the ocean varies as a result of variations in three primary factors: phytoplankton and algae, suspended inorganic sediment, and both dissolved and particulate detrital pigments. The patterns and variations in these three groups both result from impacts of climate and may also influence climate. A potential feedback between the ocean biology and the climate system involves carbon budgets. Phytoplankton fix carbon, but the timing and intensity of ocean blooms depends on climatic factors, such as upwelling, runoff, and mixing of the ocean. Detrital pigments transport carbon from land to the ocean, and can lead to loss of carbon to the ocean floor. Ocean color data from satellites help in identifying the magnitude of these processes.

A Brief History

The ocean is much darker than land and the atmosphere, so remote sensing of ocean color is more difficult than land features. However, ocean color from space started with Landsat-1, launched in 1972. The first Landsat series, with the Multispectral spectrometer (MSS) had bands that measured green, red, and reflected near-infrared light with a nominal pixel size of 80 m, and a repeat of every 18 days. While this sensor was not intended for ocean applications, it was found useful in identifying turbidity patterns in estuaries. With Landsat-4, launched in 1982, the Thematic Mapper was added. This sensor added a blue band and increased the resolution to 30 m. It has proved useful in examining structure of coral reefs, as well as seeing patterns of river plumes. The AVHRR, operating at a relatively coarse 1 km resolution, is another sensor that provides information on ocean color, although it had never been designed to do so. However, AVHRRs enable near-real time monitoring by providing observations every day, limited only by clouds.

The first sensor designed specifically for ocean color observations was the Coastal Zone Color Scanner (CZCS), launched in November 1978 on the Nimbus-7 satellite. It was about ten-fold more sensitive than Landsat, and could collect data every few days, with a ground pixel size of about 800 m. The CZCS provided an extraordinary data set for the first three years, and continued operating until 1986. The CZCS has been used extensively to estimate phytoplankton biomass and primary productivity over large regions of the ocean. Despite the value of CZCS, it was 10 years before other sources of ocean-color data were launched, with the Moderate Optoelectrical Scanner (MOS), the Ocean Color and Temperature Scanner (OCTS), and the POLarization and Directionality of the Earth's Reflectances (POLDER) instrument.

In 1997, with the launch of the Sea-viewing Wide Field of View Sensor (SeaWiFS) on the commercial satellite OrbView-2, came the first ocean color mission with a goal of routinely and continuously characterizing global ocean color. SeaWiFS was configured to collected data at 1-km in a local mode, but also to collect data globally at 4 km resolution making it the first satellite specifically designed to routinely collect ocean color data for the world ocean. (http://oceancolor.gsfc.nasa.gov). It provides details on both global and local scales to highlight individual events as well as seasonal to interannual variability, including such global phenomenon as the ENSO impacts on biomass in the ocean. A climatology created using SeaWiFS data between 1998 and 2003 is shown in Figure 3. The MODIS sensor, with bands similar to SeaWiFS, also determines ocean color and was launched on NASA's Terra satellite in late1999 and on Aqua in 2002.

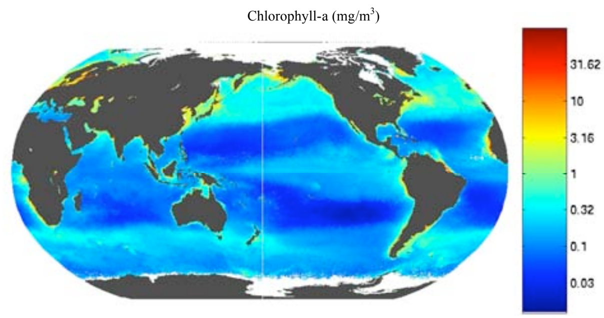

Figure 3: Chlorophyll-a climatology for April based on SeaWiFS v4 data from 1998-2003.

Current Status and a Look Forward

As of early 2006, SeaWiFS is still operating and producing high quality data. Since SeaWiFS is commercially owned, availability of SeaWiFS depends on purchasing licenses. Currently NOAA and NASA have covered global licenses to the end of 2006. Ocean color observations from MODIS on Aqua have been fully calibrated and now provide global data of a quality comparable to SeaWiFS (http://oceancolor.gsfc.nasa.gov). The sensor is the prototype for the VIIRS instrument that will fly on the next generation NPOESS environmental satellites, starting about 2009 with the launch of the NPOESS Preparatory Project spracecraft. For a list of other sensors providing ocean color data of various resolutions and quality, see the International Ocean Colour Coordinating Group (IOCCG) website (http://ioccg.org).

Critical Activities

Development and application efforts are underway in many parts of the world, with the IOCCG sponsoring many working groups focused on items like ocean color algorithms, sensor calibration, and the merging of ocean color data from multiple sensors. Implementing these activities and applying them consistently over the ocean color time series is critical in developing CDRs for these important parameters.

Ocean Surface Topography

Why Observe Ocean Surface Topography?

Space-borne altimeters provide long-term global measurements of the ocean's surface topography. In a dynamical sense, sea surface height measurements are analogous to the surface atmospheric pressure measurements used in numerical weather models. Large-scale ocean surface currents are in geostrophic balance with the slope of the sea surface. For inter-annual to decadal time scale phenomena, such El Nino/Southern Oscillation and the North Atlantic Oscillation, these measurements provide a uniquely valuable way of monitoring circulation and heat content changes of the upper ocean associated with changes in sea surface height.

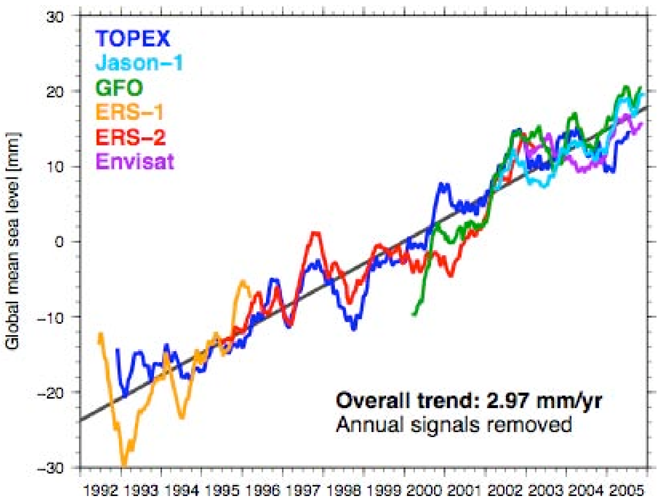

Figure 4: Global mean sea level determined by TOPEX, Jason-1, Geosat-Follow-On (GFO), ERS-1, ERS-2, and Envisat radar altimeters

On time scales greater than a decade, the near global coverage provided by satellite altimeters makes it possible to estimate global sea level rise. By paying careful attention to instrumental and environmental (e.g. path delay) corrections normally applied to an altimeter's range measurement, it is possible to construct a consistent record of global mean sea level change from six different altimeter missions over the past fourteen years. As shown in Figure 4, the overall trend for this interval is 2.97 mm/year, roughly 50% greater than the ~2.0 mm/year rate of rise observed over the past century from tide gauge measurements (Scharroo et al., 2006). Whether this rate increase reflects a true long-term change or simply decadal variability is presently unknown. Regional variations in sea level trends around the globe are shown in Figure 5.

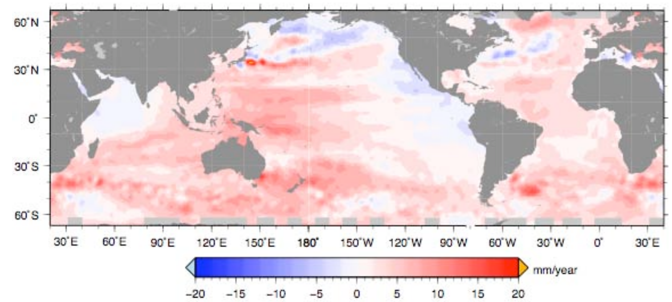

Figure 5: Regional sea level trends over Jan 1993 - Feb 2006 from TOPEX and Jason-1 satellite altimeter observations. The global mean of this map is the same as the six-altimeter solution shown in Figure 4.

A Brief History

Radar altimetry from space began in the late 1970s with the GEOS-3 and SeaSat missions, but the first useful altimeter for the climate record, both in terms of measurement accuracy and record length, was the U.S. Navy's Geosat mission (1985-1989). Unfortunately there is a 2 year gap between Geosat and the next subsequent mission, the European Space Agency's ERS-1 beginning in 1991, which prevents a cross-calibration between the missions. ERS-1 and the launch of the NASA/CNES Topex/Poseidon mission in 1992 began the uninterrupted altimetric record that continues up to the present. Topex/Poseidon provided data until October 2005, yielding an unprecedented 13-year record of high accuracy sea surface height data.

Current Status and a Look Forward

Currently there are three fully functional satellite radar altimeters, each flying in a different orbital configuration: Jason-1, the successor to Topex/Poseidon (10-day repeat period, 66° inclination); Geosat Follow-on, the successor to Geosat (17-day repeat period, 108° inclination); and Envisat, the successor to ERS-1 & ERS-2 (35-day repeat period, 98° inclination). Ocean surface topography data from these sensors is now widely available (see for example http://podaac.jpl.nasa.gov/ost and http://www.aviso.oceanobs.com/html/donnees/welcome_uk.html). Because altimeters provide height measurements only at the nadir location along their ground track (and not a 'swath' of data, as is typical of other satellite instruments) there is always a trade-off between spatial and temporal resolution. Fortunately, for the large-scale processes generally of interest for climate observations, a single high-accuracy altimetry mission such as Topex/Poseidon and Jason-1 is sufficient. The next such mission will be Jason-2/OSTM (Ocean Surface Topography

Mission), which is scheduled for launch in mid-2008 and will replace Jason-1 to continue the long time series begun by Topex/Poseidon. Shorter space and time-scale phenomena at the ocean's mesoscale are not adequately sampled by a single altimeter, but the present configuration of three complementary altimeters does capture most of the signals of interest. Applications such as ocean eddy monitoring, surface current analyses, and ocean heat content for hurricane intensity forecasting require this higher resolution sampling (see http://ibis.grdl.noaa.gov/SAT for more information on altimetry research and applications). In the next few years, however, it is likely that Geosat Follow-On and Envisat will cease without replacement, and there will only be one operational altimeter – Jason-2/OSTM.

Critical Activities

To insure the accuracy and value of altimeter observations for climate studies, particularly for the global sea level rise problem, it is important to have a period of overlap between satellite missions. Only by directly comparing the average heights between missions is it possible to accurately detect and correct for offsets and thereby extend the global sea level record over multiple decades. An overlap is also useful for identifying subtle instrument dependent problems, such as a drift in one of the environmental corrections to the range measurements. A problem of this type was detected in the Jason-1 microwave radiometer measurements, during the 4-year overlap between the Jason-1 and Topex/Poseidon missions. A method of compensating for this drift has now been put into place.

The value of satellite altimeter observations for climate studies is also greatly enhanced by the operation of two in situ ocean observing systems supported by the NOAA Office of Global Programs (OGP): a global network of GPS-controlled tide gauge stations, and the ARGO profiling drifter array. Relative sea level observations from more than 80 tide gauge stations are currently providing an independent, ground-based check on the stability of each satellite altimeter mission. Routine comparisons between gauge and altimeter measurements show that altimeter-measured trends are accurate within +/-0.4 mm/year. Thus, the 2.97 mm/year trend observed over the past decade by satellite altimetry (Figure 4) is significantly higher than the gauge-measured trend over the past century.

The ARGO profiling system provides an important, complementary set of climate observations: global measurements of the vertical density structure of the ocean. An altimeter measures sea surface height, which is a function of the both the mass and vertical density structure of the ocean at a given location. By combining these two data sets, one can obtain a complete description of the state of the ocean, the holy grail of ocean climate monitoring. One problem that may soon become accessible through the combination of these two data sets is that of determining how much of global sea level rise is due to thermal expansion versus the addition of new water to the oceans due to the melting of continental ice.

Ocean Surface Winds

Why Observe Ocean Surface Winds?

The observation of marine winds from space-borne instruments provides a global measure of the fluid dynamics in the lower atmosphere where the impact of climate is felt most directly. Such observations lead directly to the ability to track and understand significant environmental events, such as tropical storms, and to monitor their intensity variations. From a more inclusive perspective, marine winds are the dynamic coupling link between the ocean and the atmosphere, providing fundamental information for understanding the energy and momentum exchanges across the air/sea boundary. A consistent, long term, and global record of these winds is fundamental for monitoring and modeling climatological phenomena.

A Brief History

The satellite instruments that measure ocean surface winds fall into three types: microwave radiometers, scatterometers, and synthetic aperture radars (SAR). The first two have reached advanced levels where CDRs can be generated with global coverage, while SAR is generally used to measure specific, isolated environmental events.

Microwave radiometers are particularly well quantified, the most historically notable being the Special Sensor Microwave Imager (SSM/I). Since 1987 the Defense Meteorological Satellite Program (DMSP) has flown this instrument on a series of satellites and presently has three functioning operationally that provide full global ocean surface wind speed coverage in less than 24 hours. In 2003 the Special Sensor Microwave Imager Sounder (SSMIS), the next generation of SSM/I, was launched and presently has data available. Other advanced radiometers capable of measuring ocean surface wind speed include the TMI and the AMSR-E, which also provide contemporaneous measurements of SST as discussed earlier. Among the most unique instruments to have been recently placed in orbit, however, is WindSat on the Coriolis satellite in January of 2003. WindSat uses polarimetric capabilities to resolve the full ocean surface wind vector including both speed and direction.

SKYLAB operated the first scatterometer in space, the S-193, in 1973 and 1974, demonstrating the feasibility of using scatterometers to measure ocean surface winds. The SeaSat-A Satellite Scatterometer (SASS) onboard the SeaSat oceanographic satellite followed in 1978. Although SASS operated for only 100 days, the data obtained was successfully used to generate accurate ocean surface wind velocity measurements. The European Space Agency (ESA) successfully demonstrated the operational advantages of scatterometers with their ERS-1 and ERS-2 satellites, launched in 1991 and 1995 respectively.

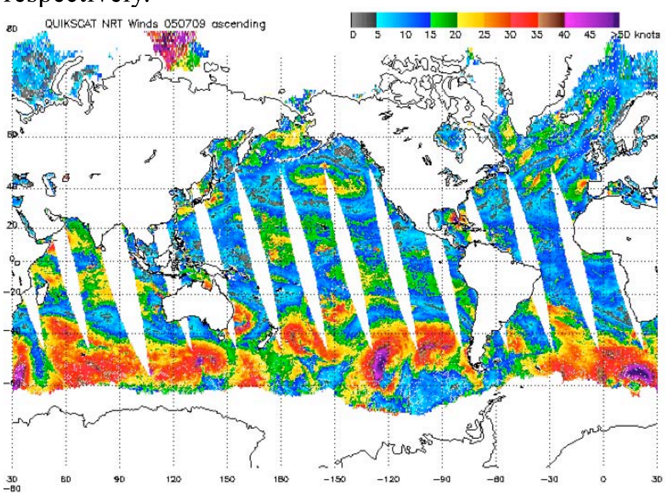

Figure 6: Global QuikSCAT Winds showing single day coverage by ascending pass.

NASA launched its NASA Scatterometer (NSCAT) aboard the ADEOS satellite in 1996. NSCAT operated flawlessly for 9 months, providing data for the production of ocean surface wind vector fields with a 25 km spatial resolution, before suffering a catastrophic power failure on May 9, 1997.

To minimize the temporal data gap, NASA put forth the Quick Scatterometer (QuikSCAT) mission to place and maintain a scatterometer in orbit until the launch of ADEOS II (see Figure 6 for plot of daily coverage by QuikSCAT). A SeaWinds scatterometer was used on the QuikSCAT satellite, which was launched in July of 1999 and has been operational since. The QuikSCAT mission proved to be not only a scientific and operational success, but absolutely invaluable to the remote sensing community as ADEOS II failed roughly 9 months after it became operational in October of 2003.

Current Status and a Look Forward

Although NSCAT on ADEOS and SeaWinds on ADEOS II operated for 18 months, QuikSCAT has provided almost seven years of continuous data and presently carries the only microwave scatterometer capable of global ocean surface wind measurements. The Advanced Scatterometer Instrument (ASCAT) of the European Space Agency's MetOp mission offers the most immediate plan for another wind measuring scatterometer in space. WindSat continues to produce high quality wind fields of comparable resolution to QuikSCAT, but is still fundamentally part of a scientific proof-of-concept mission. The CMIS, part of the NPOESS instrument collection to launch around 2010, is a future polarimetric radiometer designed to operate on similar principals as WindSat.

Critical Activities

The remarkable duration of the QuikSCAT mission has brought satellite measurement of ocean wind fields into the realm of climate science, allowing CDR production to be routine in a weekly and monthly temporal basis, such as the weekly and monthly QuikSCAT global wind fields created by Remote Sensing Systems. Previous to QuikSCAT, the measured global ocean surface wind vector field was scattered temporally and spatially at best, with ERS-1 and ERS-2 offering globally distributed measurements, but with a narrow swath. QuikSCAT is approaching an unprecedented seven years of continual operations, but has no reliable U.S based replacement set to compliment or continue this record production. A wind speed climatology for the month of April is shown in Figure 7, based on 1999-

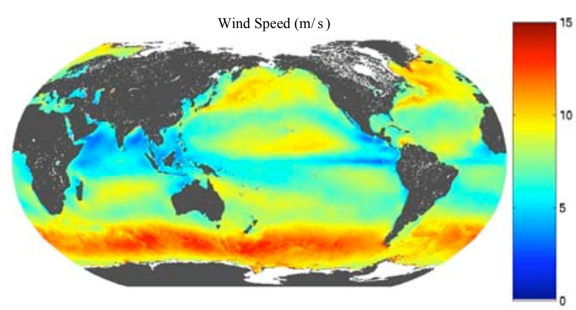

Figure 7: QuikSCAT Winds speed climatology for April, from 1999-2004 data. See http://data.nodc.noaa.gov/pathfinder/NODC_QuikSCAT_Winds for more information.

2004 QuikSCAT data. A meaningful CDR wind field obviously requires a reasonably unbroken data flow. The ASCAT instrument on the first of the MetOp satellites, to be launched in 2006, will do much to compliment the present ocean wind field climate record and prevent a gap in the data flow. Also of significance is the cross-validation of different surface wind measuring platforms, such as the C-band ASCAT scatterometer, the Ku-band SeaWinds scatterometer, and more varied instruments such as the polarimetric radiometer WindSat. Included in this is more sophisticated validation of measurements of extreme environmental events, such as tropical storms and hurricanes, with more localized measurements using similar scatterometers and radiometers aboard NOAA WP-3D aircraft. As the remote sensing community is still in a learning phase for using passive polarimetric techniques, such studies and validation are crucial for understanding the cross-calibration/validation issues of wind measuring scatterometers and radiometers and how to exploit the benefits of both instrument types for a more complete marine wind field climate record.

Sea Ice

Why Observe Sea Ice?

Most climate models predict polar amplification of warming – that is, polar regions experience climate change sooner and more intensely than mid latitudes. For this reason scientists have long been interested in monitoring sea ice as a climate indicator. From a climate perspective, Arctic sea ice is more interesting since it plays a greater role in oceanic and atmospheric circulation than Antarctic sea ice, which also occupies only a relatively small area south of 75° South.

Over time, warming reduces the volume of sea ice. Thinner sea ice, or ice covering less area, modifies climate by insulating the atmosphere from the ocean less. In winter's polar night, breaks in the sea ice cover release heat and moisture to the atmosphere; in summer's continuous daylight, reductions in ice concentration (the percentage of an area covered by ice floes) enhance heat flux from solar radiation into the ocean. Sea ice, like snow, is a high albedo surface that reflects incoming solar radiation. Sea water, by contrast, is dark and absorbs much more radiation. Modeling ice-albedo feedback (where less ice leads to more heat absorption in the ocean which leads to less ice, and so on) is a critical aspect of General Circulation Models (climate models).

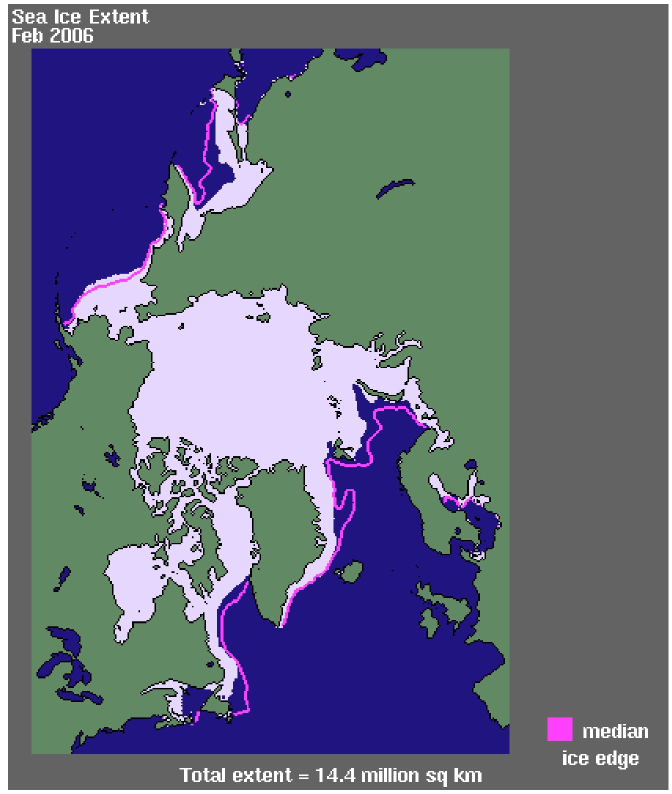

*Figure 8: Sea ice extent for February shown with the climatological (1979-2000) median extent. The characteristic Odden shape appears in the median north of Iceland and east of Greenland. Extent anomaly image from the Sea Ice Index (**http://nsidc.org/data/seaice_index**).*

Sea ice has a role in oceanic circulation, the "conveyer belt" of heat transport, as well. As new ice grows, it releases brine into the upper layer of the ocean and increases the density of the water. Under the right conditions, cold, super dense water forms and sinks below the mixed layer to great depths, serving as a driver for thermohaline circulation. The Odden (Norwegian for headland), a tongue of ice that sporadically forms off the east Greenland ice edge in winter, is associated with this type of deep water convection. Although recent work has shown that an Odden event is not a requirement for deep water convection, the reduction, since the 1980s, in the frequency with which the Odden appears has caused concern (Figure 8).

A Brief History

Sea ice and ocean water have dramatically different electromagnetic signatures in microwave, infrared, and visible-band data, making satellite imagery of sea ice relatively straightforward to interpret. Operational ice services use satellite data from variety of sources to manually construct analyses. Passive microwave data have proven most useful for climate data records, since ice concentration estimates are not affected by cloud cover and the polar night, and more than 30 years of data are now available. The single channel Electrically Scanning Microwave Radiometer (ESMR) launched on Nimbus-5 in 1972; the Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7 provided data from 1978 until 1987; the time series from the Defense Meteorological Satellite Program Special Sensor Microwave/Imager (DMSP SSM/I) sensors began in 1987 and is ongoing; and the future NPOESS CMIS instrument is intended to continue the record.

Most sea ice data sets are based on algorithms that had their genesis with NASA investigators. Data sets from two algorithms, the NASA Team (NT) and the Bootstrap (BT), are mature and widely used. Time series of sea ice extent (total ocean area containing at least 15% ice) sea ice area (total area covered by ice) and sea ice concentration (percentage area covered by ice) are available from the National Snow and Ice Data Center (NSIDC) on a 25 km grid (for a summary of these and other Sea Ice Products at NSIDC see http://nsidc.org/data/seaice). The NT and BS algorithms use the dual polarization 19.3 (or 18.0 in the case of SMMR) and 37.0 GHz channels. A considerable amount of work has gone into making records consistent across changes in instrumentation and platform. For example, the 1.3 GHz difference between SMMR 18.0 and SSM/I 19.3 channels results in a discontinuity in the data record of raw brightness temperatures, and a greater sensitivity to weather effects in the SSM/I data. Differences are notable even between SSM/I instruments. Only recently has the gap between the single channel ESMR, which operated until 1977, and SMMR, which began in 1978, been bridged, using ancillary data in the form of operational analyses from the National Ice Center.

Current Status and a Look Forward

Sea ice is highly variable, so deriving trends with confidence demands long records in which consistency may be more important than accuracy. For example, ice concentration from passive microwave tends to be biased low by a seasonally dependent amount, with underestimation greatest in summer, when pools of melt water, indistinguishable from ocean water to the sensor, form on the surface of the ice. Sea ice extent is less affected than is ice area, making extent a more robust indicator. The BT and NT algorithms take different approaches and yield different results, but the key characteristic of data sets from both algorithms relevant to climate data records is that they are internally consistent, with consistent biases, across changes in instrumentation. The NSIDC Sea Ice Index uses the combined SMMR-SSM/I record and NT algorithm to show trends (Figure 9) and anomalies on a monthly basis.

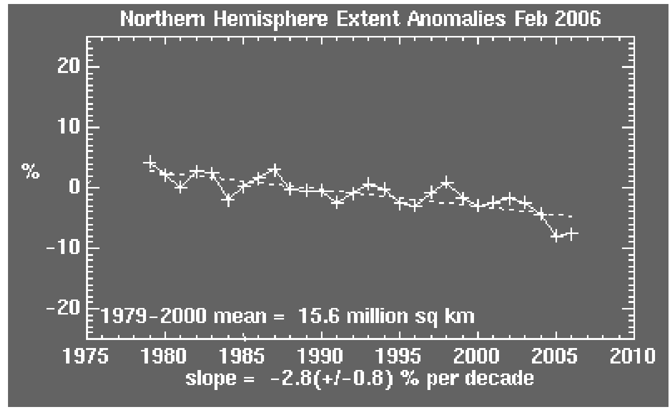

Figure 9: Extent anomaly trend for February from the Sea Ice Index (http://nsidc.org/data/seaice_index). Trends for the Southern Hemisphere are also available.

New instruments and algorithms offer hope for better accuracy. The NPOESS CMIS, like the AMSR-E now in orbit on NASA's Aqua platform, will have an 18.7 GHz channel that is optimal for reducing weather effects. AMSR-E has a resolution that is about twice that of SSM/I, and the CMIS resolution will be slightly better than that of AMSR-E. This finer spatial resolution alone improves the accuracy of concentration and extent. An algorithm called NT2 uses the higher frequency channels available on SSM/I and later sensors to overcome weather and snow effects, and is being used with AMSR-E data.

Satellite records alone give only a two dimensional view of ice, but what is most useful is sea ice volume. Obtaining ice freeboard from satellite altimetry for estimates of ice thickness is a promising technique, but for now in situ instrumentation is depended on for ice thickness. However, after the record 2005 minimum in ice extent, confidence is growing that the decline in ice extent reflects a significant loss in ice volume as well (see Sea Ice Decline Intensifies at http://nsidc.org/news/press/20050928_trendscontinue.html; a joint NSIDC, NASA, and University of Washington press release).

Critical Activities

In the past, NOAA/NASA Polar Pathfinder funding was crucial to the development of the SMMR-SSM/I time series. A similar effort is needed to extend SSM/I with CMIS, and should include research with AMSR-E to prototype CMIS ice products. NPOESS is not planned for launch until years after the Aqua design life ends in 2008, likely leaving a gap between AMSR-E and CMIS coverage. DMSP should cover this gap, but the operational nature of the DMSP program has meant that overlaps between sensors have been short. The intercalibration of SMMR and SSM/I ice records is based on only a six-week overlap period in 1987 when both sensors operated. Short overlap times impinge CDR quality; an overlap of at least 1.5 years (covering all seasons in both hemispheres) provides substantially better capability to account for sensor differences.

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